First measurement of the Top quark mass in pp collisions at $s^{1/2}$=7 TeV

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On behalf of the CMS Collaboration

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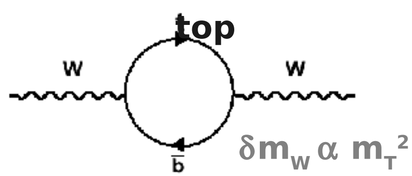
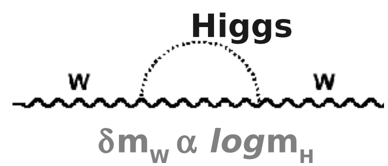
Introduction: why measure m_{top}?

- The **top quark mass is a fundamental parameter** of the Standard Model (SM)
  - Known with great accuracy from the Tevatron: **173.3 ± 1.1 GeV/c²** arXiv:1007.3178v1

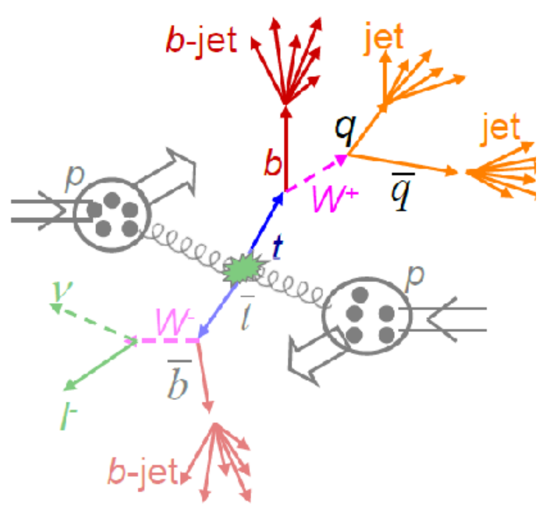
    (but has never measured outside the Tevatron until now)
  - Indirect constraint on the Higgs boson mass via EW corrections Higgs mass

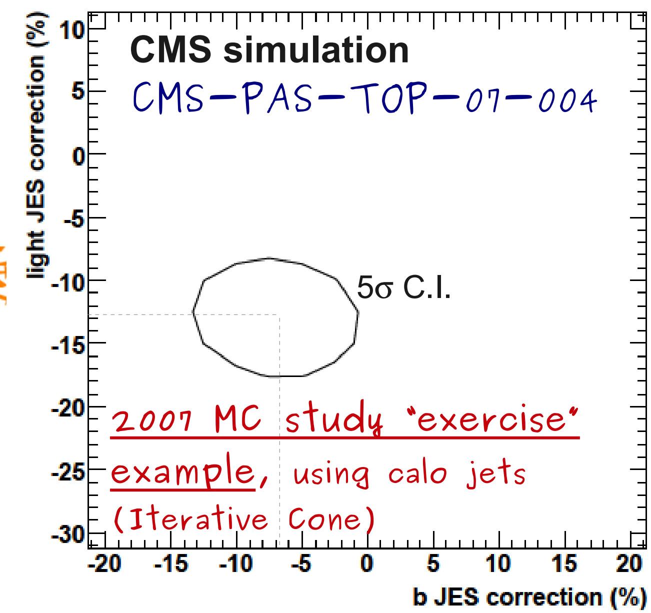




- **Measuring precisely m_W and m_{top}**
  - Test the consistency of the SM
  - Search for new Physics
  - **Calibrate the detectors: determine jet energy scale**

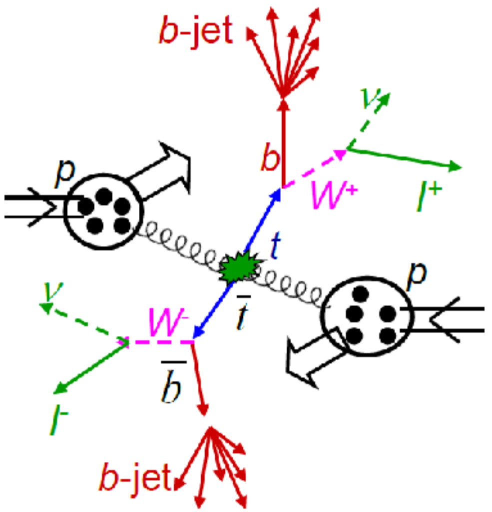
    (only process which can calibrate the b-jet energy scale)





Main challenges in measuring m_{top} in the dilepton channel

- **The dilepton channel is chosen for this measurement ▸**
  - Lowest statistics BR ≈ 5/81
  - **Distinct signature, background is small**
- **Reconstruct final state products ⇒ reconstruct bare mass**



$$\sigma(m_{top}) \sim \frac{\Delta m/m}{\sqrt{N_{good\ assignments}}}$$

Combinatorics

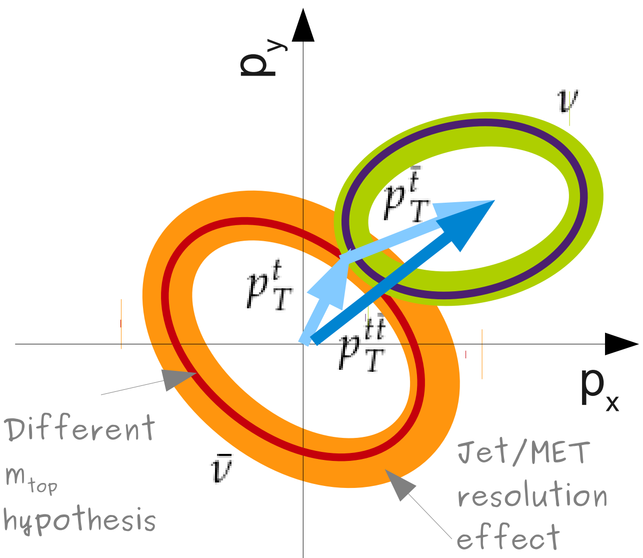
- ISR/FSR introduces further complexity for selection
  (≈70% of the events expected to have both b-jets)

Missing transverse energy

- 2 neutrinos constrained in the transverse plane ⇒ $\vec{E}_T^{miss} = \vec{p}_T^{\nu} + \vec{p}_T^{\bar{\nu}}$

Jet energy scale/resolution

- m_{top} reconstruction requires measuring the parton energy



Event selection

Two leptons, at least two jets

and missing transverse energy

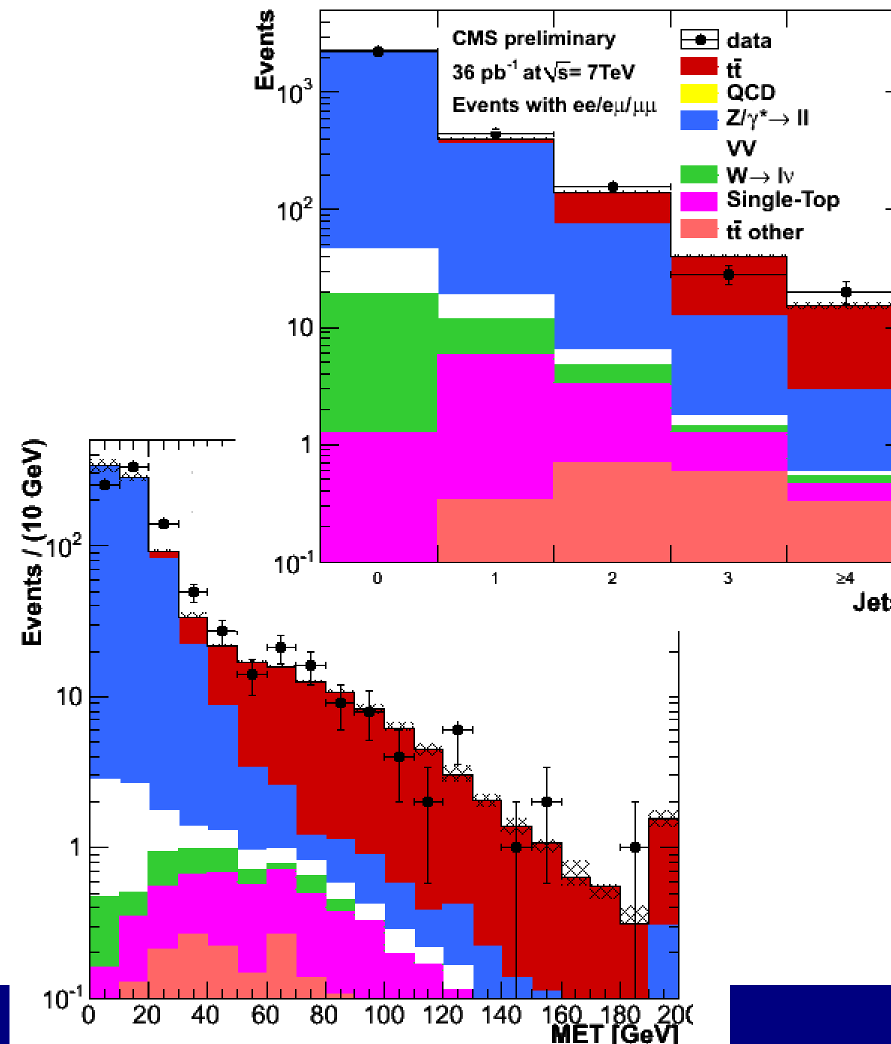
are required to select $t\bar{t} \rightarrow (l^-\bar{\nu}_l b)\ (l^+\nu_l\bar{b})$

from pp collisions at $s^{1/2}$=7 TeV

Note: for details on the CMS detector cf. K. Hoepfner's talk

Event selection

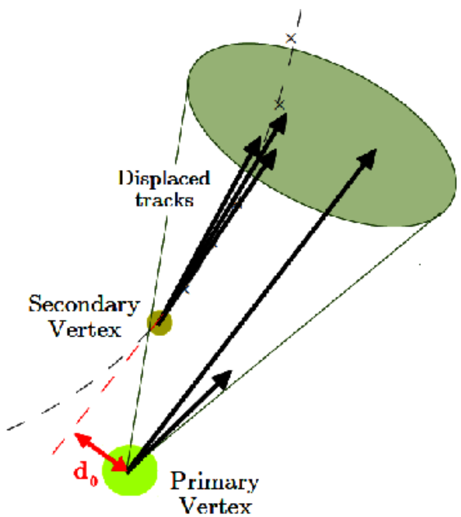
- **Inclusive single lepton trigger ▸**
  - Most data triggered by: muon with p_T>15 GeV/c (μμ/eμ) or electron with E_T>17 GeV (ee/eμ)
- **≥ 2 leptons,** p_T>20 GeV/c |η|<2.5
  - Isolated and promptly produced
- **Leading Σp_T op. sign dilepton**
  - M>12 GeV/c² and $|M-M_Z|$>15 GeV/c² for ee/μμ
- **≥ 2 jets,** p_T>30 GeV/c |η|<2.5
  - Anti-k_T (R=0.5), particle flow based algorithm
- **MET > 30 (20) GeV** for the ee/μμ (eμ) channel

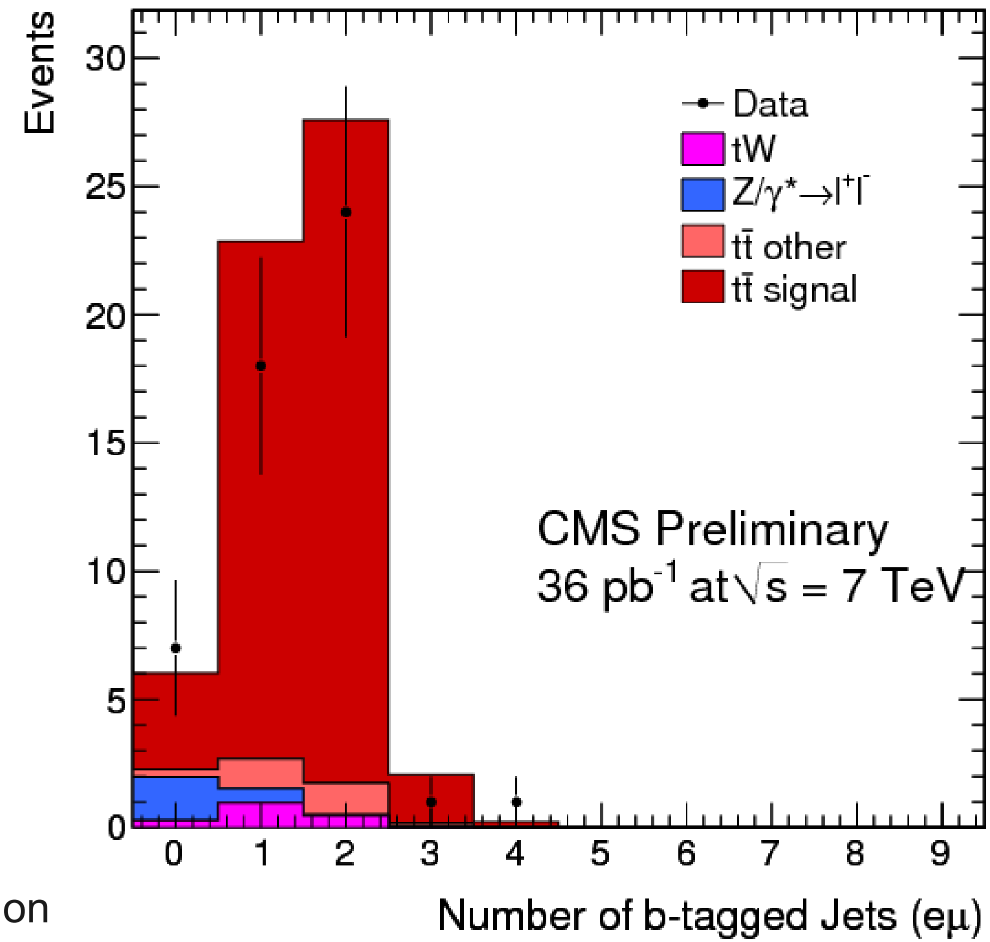


b-tagging information

Good agreement of b-tag multiplicity is observed

b-tagging is not used in the event selection





- **b-tagging information is used to rank the jets which enter the mass reconstruction**
- Jets in the selected sample can be b-tagged
  - Loose discrimination (ε_b~80% / ε_q~10%)
  - Prefer b-tagged jets for top mass reconstruction
  - Increases good jet assignment rate by 16% with respect to a p_T based choice

Selected dilepton sample

m_{top} measurement is based on the 102 events selected in data

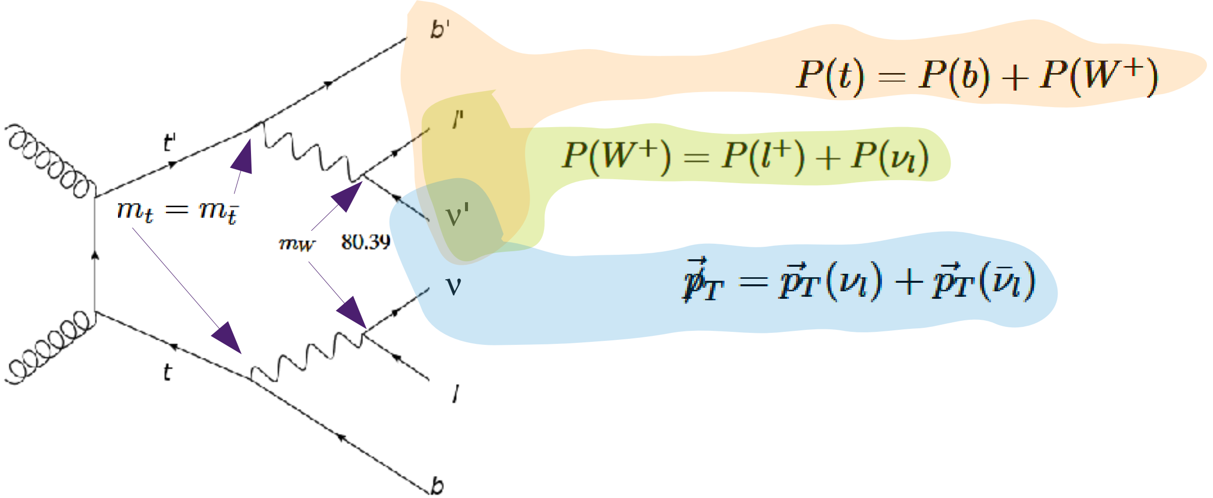
Use 36 pb^{-1} of integrated luminosity

Close agreement with direct MC expectations

Selection cut	Data	Total expected	$t\bar{t}$ signal	Total background
pre-tagged sample				
$\geq$2 isolated leptons	27257	28934 ± 49	158.8 ± 0.9	28775 ± 49
opposite sign	26779	28545 ± 42	157.3 ± 0.9	28388 ± 42
Z/quarkonia-veto	2878	2873 ± 27	139.3 ± 0.8	2734 ± 27
$\geq$2 jets	204	193 ± 2	103.1 ± 0.7	90 ± 2
$\not{E}_T$	102	$108.5 \pm 0.9\,^{+3}_{-2}$	$92.1 \pm 0.7\,^{+2}_{-1}$	$16.3 \pm 0.7\,^{+1}_{-1}$
b-tagged sample				
$= 0$ b-tag	19	$15.9 \pm 0.6\,^{+13}_{-8}$	$6.9 \pm 0.2\,^{+7}_{-3}$	$9.0 \pm 0.6\,^{+6}_{-5}$
$= 1$ b-tag	35	$40.9 \pm 0.5\,^{+17}_{-14}$	$35.7 \pm 0.4\,^{+9}_{-8}$	$5.1 \pm 0.4\,^{+8}_{-6}$
≥ 2 b-tags	48	$51.7 \pm 0.5\,^{+14}_{-16}$	$49.5 \pm 0.5\,^{+11}_{-15}$	$2.2 \pm 0.2\,^{+3}_{-1}$

Top Mass Measurement

The top quark mass is reconstructed from
the dilepton, the two *b* jets and the neutrinos
whose momenta are constrained by the MET measurement

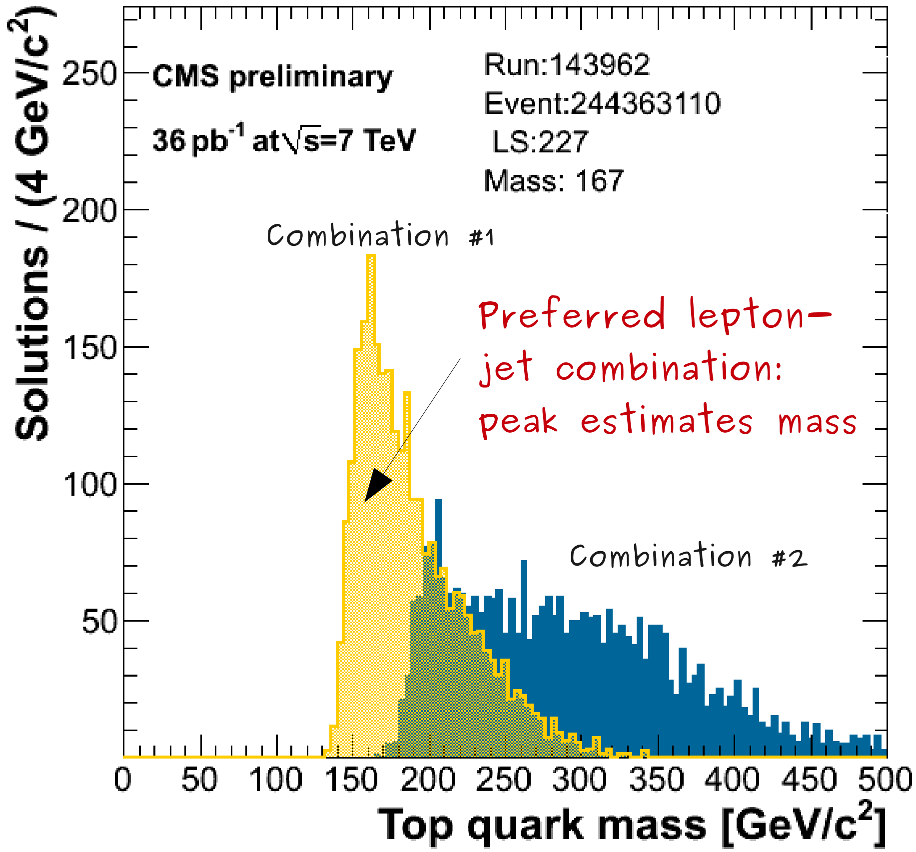


Top mass reconstruction*

Full Kinematics Analysis (KINb)

Original method from CDF PRD 73 (2006)

- Equations are numerically solved for each **lepton-jet combination** (10^4 times)
  - Each time draw a random value for p_z(top) +p_z(anti-top) + smear jet resolution
  - Accept solutions if two decay legs agree within **Δm_{top} < 3 GeV/c²** ►



(*) Jet resolution is smeared consistently according to expectations
- Smear randomly original jet energy / MET scales and resolution
- Update MET measurement accordingly: $\vec{\not{p}}_T' = \vec{\not{p}}_T - (\Delta J_1 ES - 1)\vec{p}_{T1} - (\Delta J_2 ES - 1)\vec{p}_{T2}$

Top mass reconstruction*

Analytical Matrix Weighting Technique (AMWT)

Original method from D0 Phys. Rev. Lett. 80 (1998)

- **Iterate m_{top} hypothesis** to solve kinematic equations (100-700 GeV/c^2) for each combination
  - Up to 8 solutions can be found
  - **For each weights are assigned based on pdf and kinematic quantities** (lepton energy)

$$w = \left\{\sum F(x_1)F(\bar{x_2})\right\} p(E^*_{\ell+}|m_t)p(E^*_{\ell-}|m_t)$$

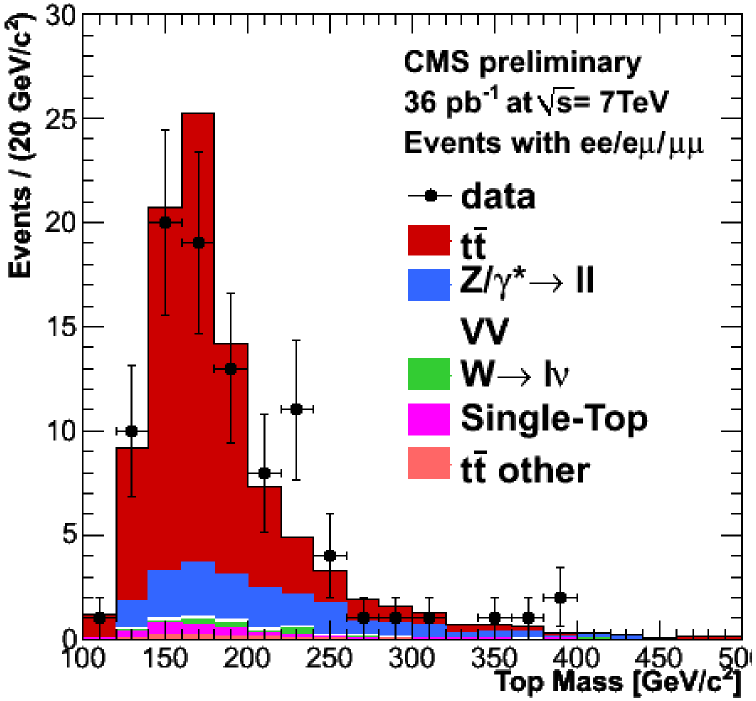
  - From **inclusive weight distribution estimate top mass** (peak)
  - No preferred lepton-jet assignment
- Process is repeated 10^3 (10^2) times in data (MC) according to expected jet energy resolution

(*) Jet resolution is smeared consistently according to expectations

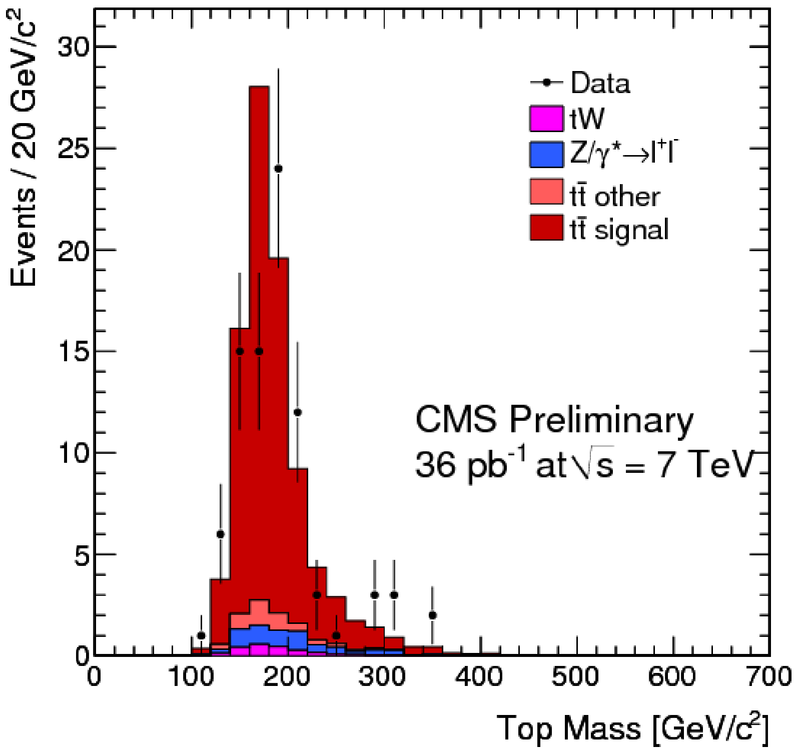
- Smear randomly original jet energy / MET scales and resolution
- Update MET measurement accordingly: $\vec{p}_T' = \vec{p}_T - (\Delta J_1 ES - 1)\vec{p}_{T1} - (\Delta J_2 ES - 1)\vec{p}_{T2}$

Top mass distributions

KINb



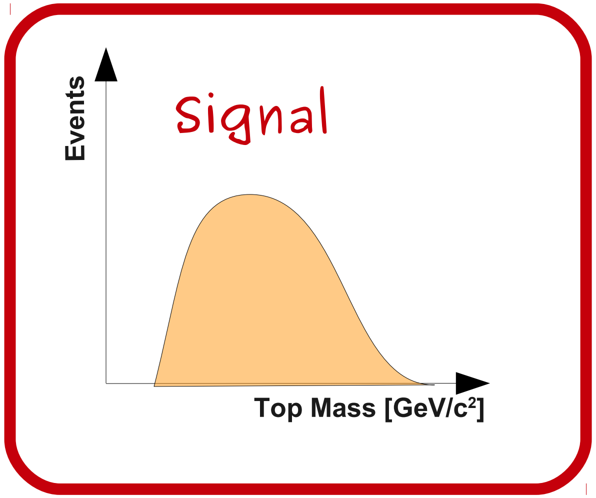
AMWT



There is an **overall good agreement** with expectations for m_{top}=172.5 GeV/c^2

For top mass measurement restrict to 100<m<300 GeV/c^2

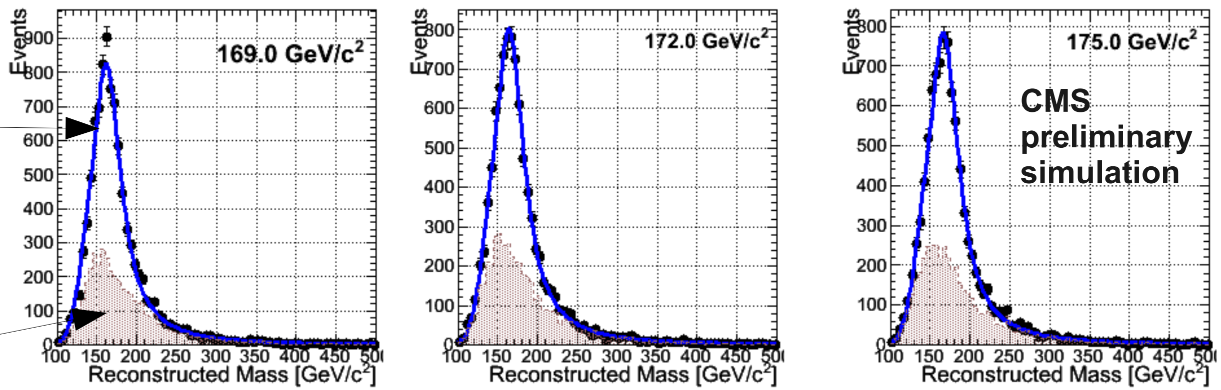
Signal modeling



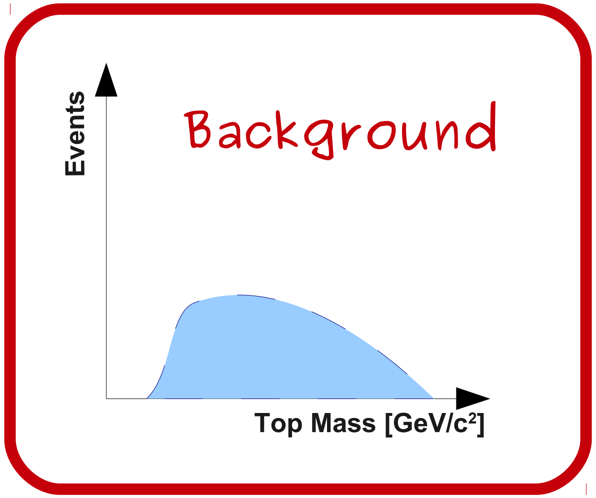
- **The signal mass template shape is modeled from MC**
  - Measurement is calibrated to the generator m_{top}
- **Use different top mass scenarios**
  - `Madgraph` based (includes full simulation of the CMS detector)
  - 151-199 GeV/c^2 covered in steps of 3 GeV/c^2
- **Signal templates**
  - **AMWT**: taken directly from MC prediction
  - **KINb**: parametrized from a combined fit (Landau+Gauss) ▼

Combined parameterization to different mass points

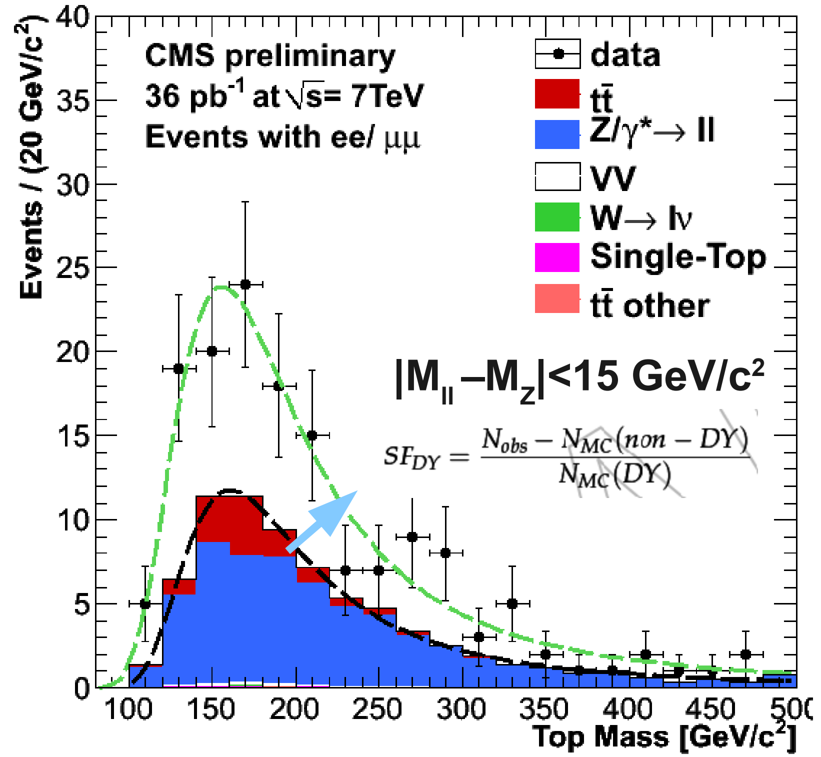
Contribution from lepton-jet misassignments in the KIN method



Background modeling



- **Background is parametrized from MC and data**
- Single top, other $t\bar{t}$, W+jets, di-boson: MC prediction
- Drell-Yan, controlled from $Z \rightarrow l^+l^-$ events



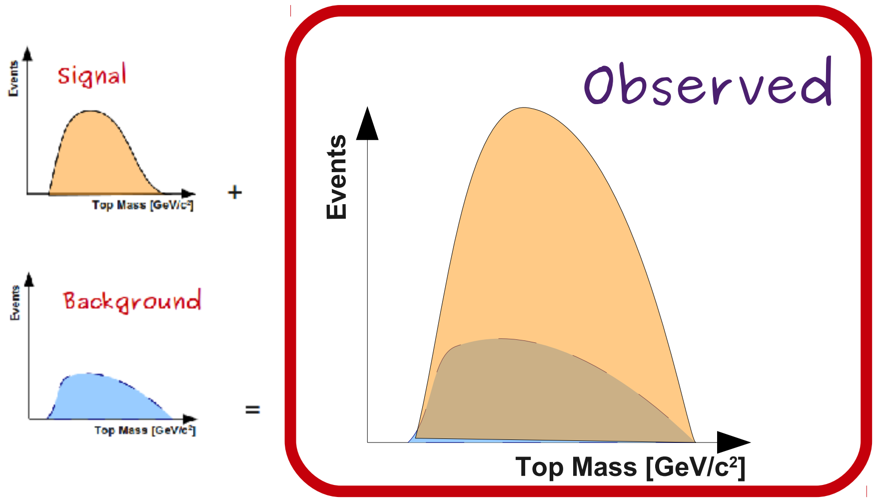
- **Re-scale DY yields to signal region from control region**

KINb: direct scale factor from “top mass” spectrum ▸

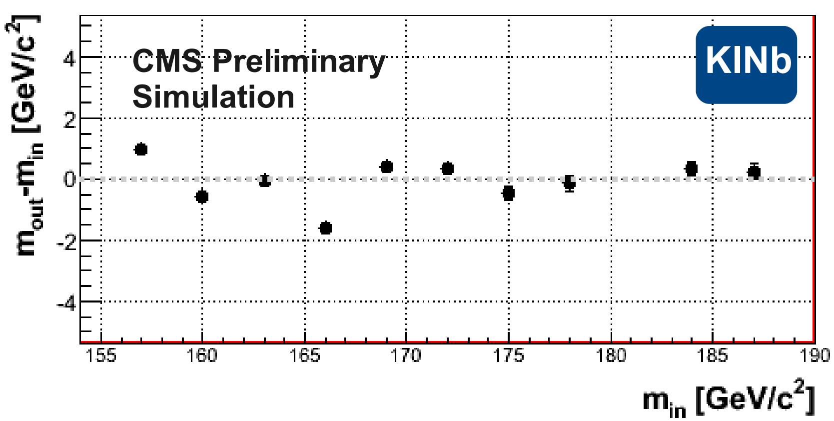
AMWT: use prediction for events outside the Z peak (R_{in}/R_{out})

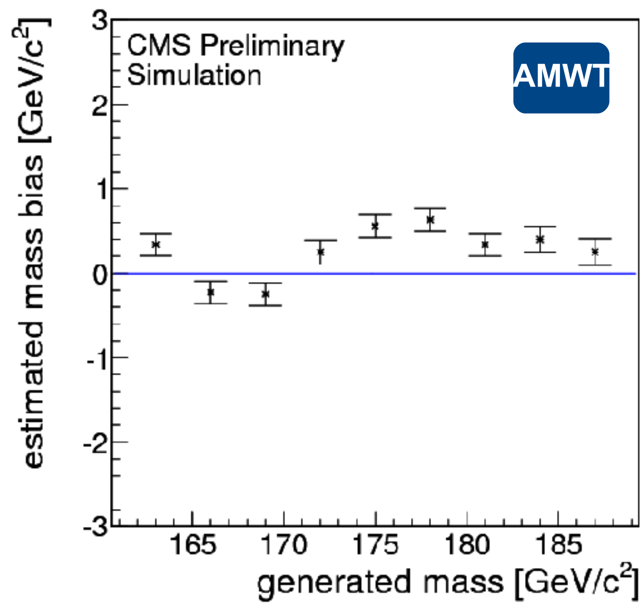
Alternative methods yield compatible results

Top quark mass fit

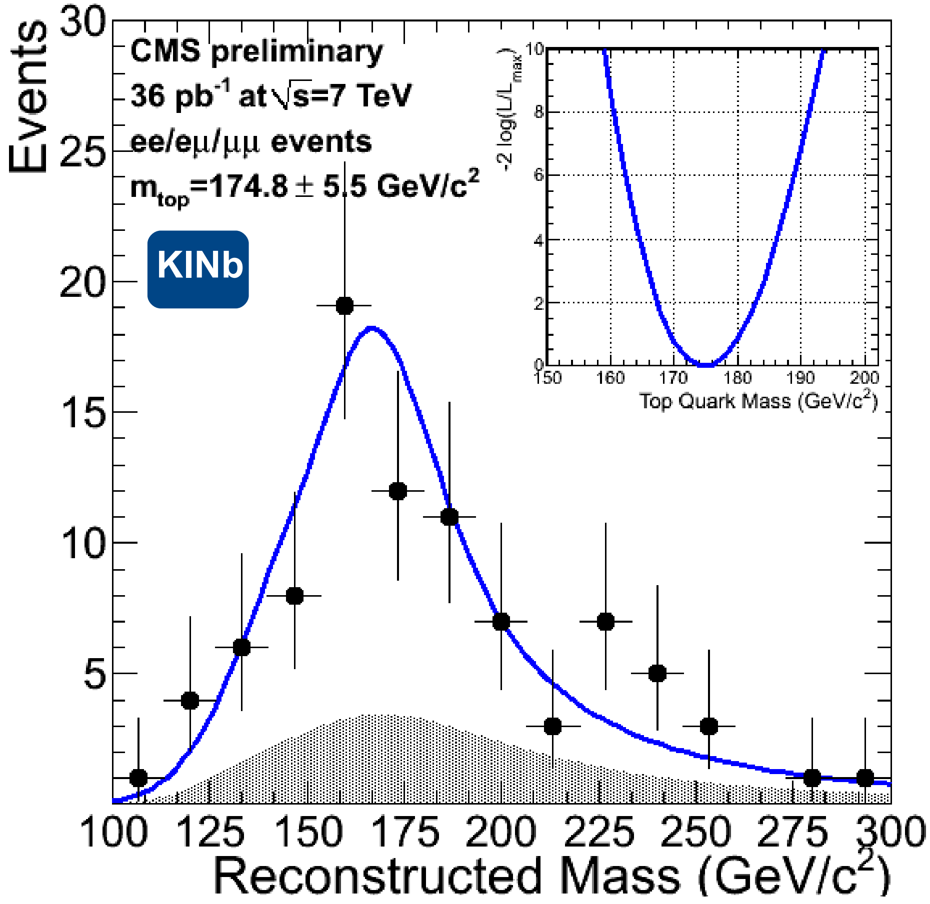


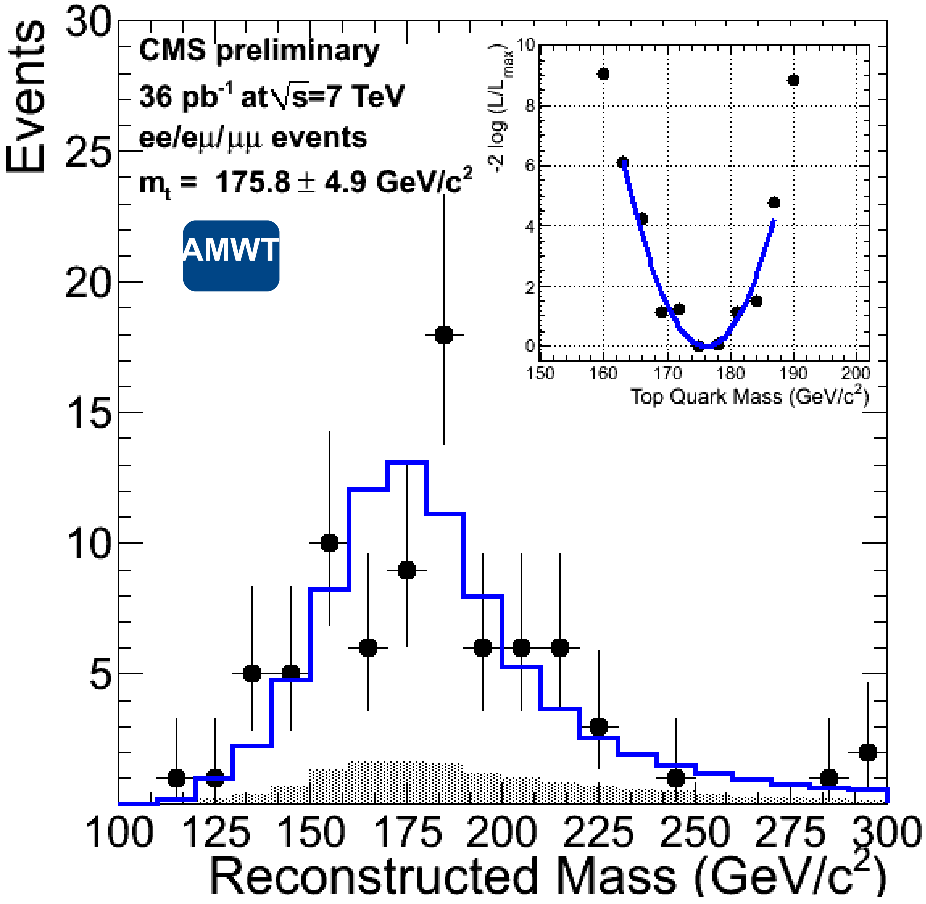
- **Apply likelihood fit to data**
- **Combine fit to events with 0, 1 or ≥ 2 b-tags**
- Both methods are expected to be linear for m_{top} measurement (i.e. $m_{out} \propto m_{in}$)
- **Minimize residual biases** with calibration of the fit to MC based pseudo-experiments





Top mass fit (results)



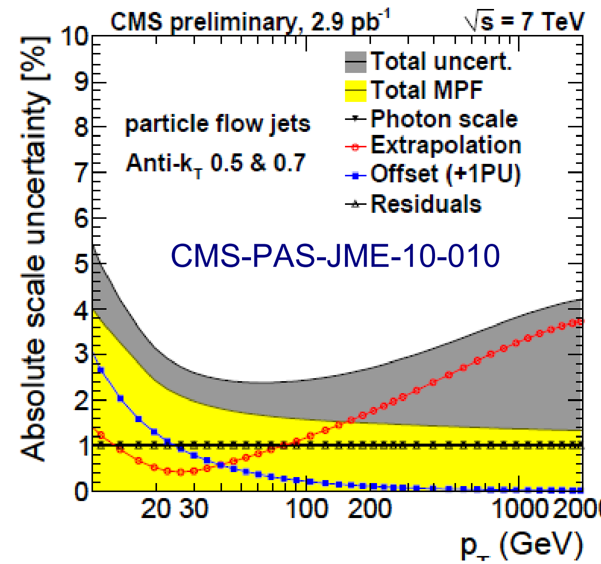


Top mass measured within the expectations with both methods.

Systematic uncertainties

(evaluated from pseudo-experiments)

- **Jet energy scale (JES) is the most relevant unc.** ▶
  - JES is varied up and down and difference in m_{top} accounted
  - **flavor (b) specific uncertainty added in quadrature**



- **MC related systematics**
  - **Difference with respect to reference sample used for signal**
    - MC : compare `Alpgen` and `Powheg` with `Madgraph`
    - Vary factorization/matching scales, amount of ISR/FSR
    - Underlying event: compare `Pythia` tunes (cf. arXiv:1010.3558v1)
  - **Pileup**
  - **PDF** - use PDF4LHC recommendation to sample new mass spectra (cf.arXiv:1101.0536v1)

- **Method specific systematics** (calibration, resolutions assumed, p_z^{tt} model)

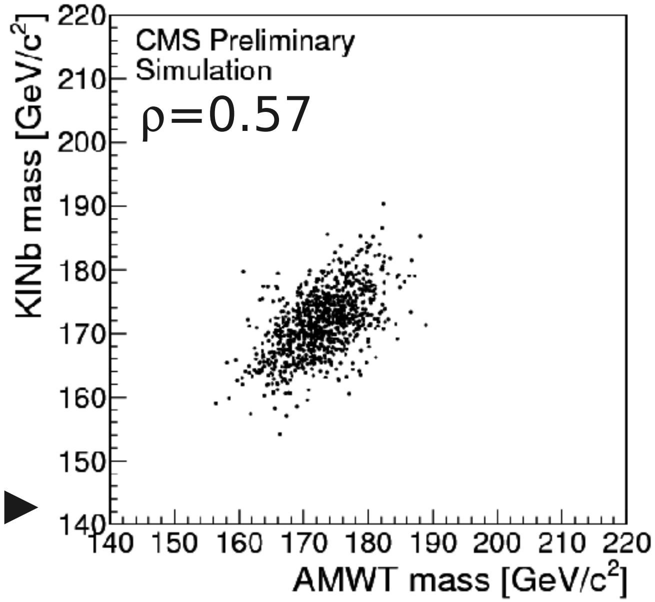
Source	KINb	AMWT
jet energy scale	+3.1/-3.7	3.0
b-jet energy scale	+2.2/-2.5	2.5
Underlying event	1.2	1.5
Pileup	0.9	1.1
Jet-parton matching	0.7	0.7
Factorization scale	0.7	0.6
Fit calibration	0.5	0.1
MC generator	0.9	0.2
Parton density functions	0.4	0.6
b-tagging	0.3	0.5

Combination of the results

- The previous **results can be combined** using a Best Linear Unbiased Estimator
- Minimize: $\boxed{S = \sum_{i,j} (m_i - m')H_{ij}^{-1}(m_j - m')}$

  H_{ij} is the error matrix which encloses the syst. uncertainty contributions (mostly fully correlated) and the stat. uncertainties.

- **Correlation factor** is determined from pseudo-experiments ▶



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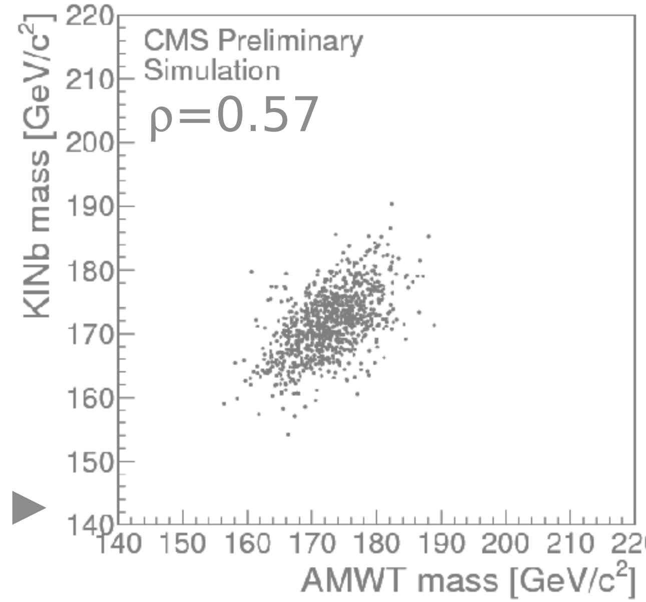

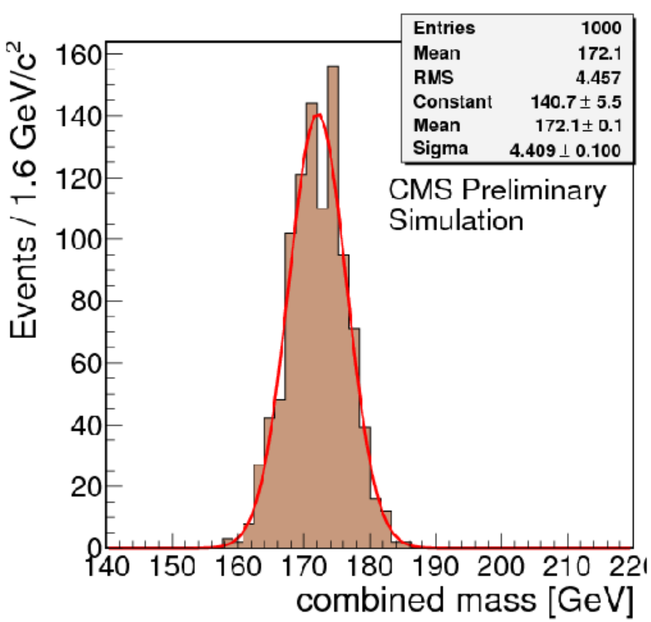

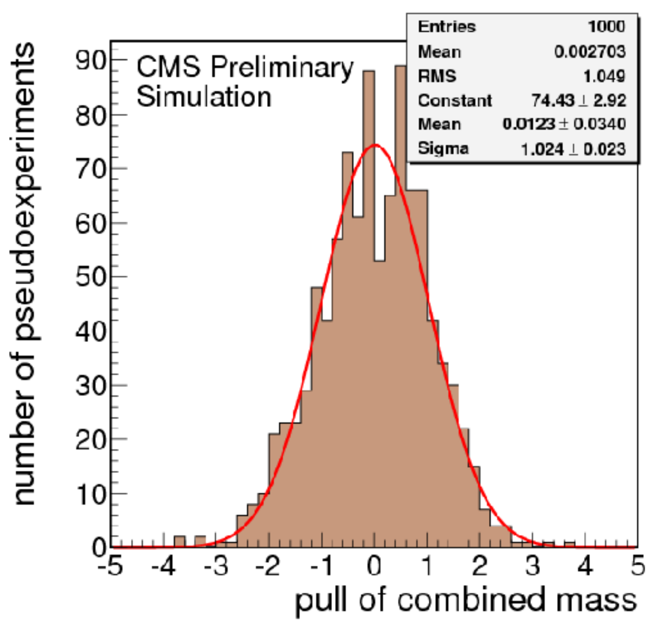

◀ Method is unbiased and the final uncertainty is correctly estimated

Result: marginal gain in the final stat. uncertainty

Combination of the results

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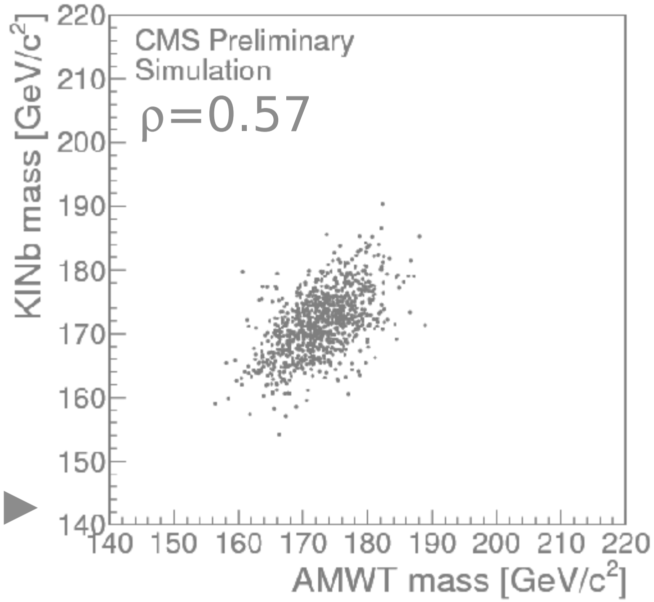
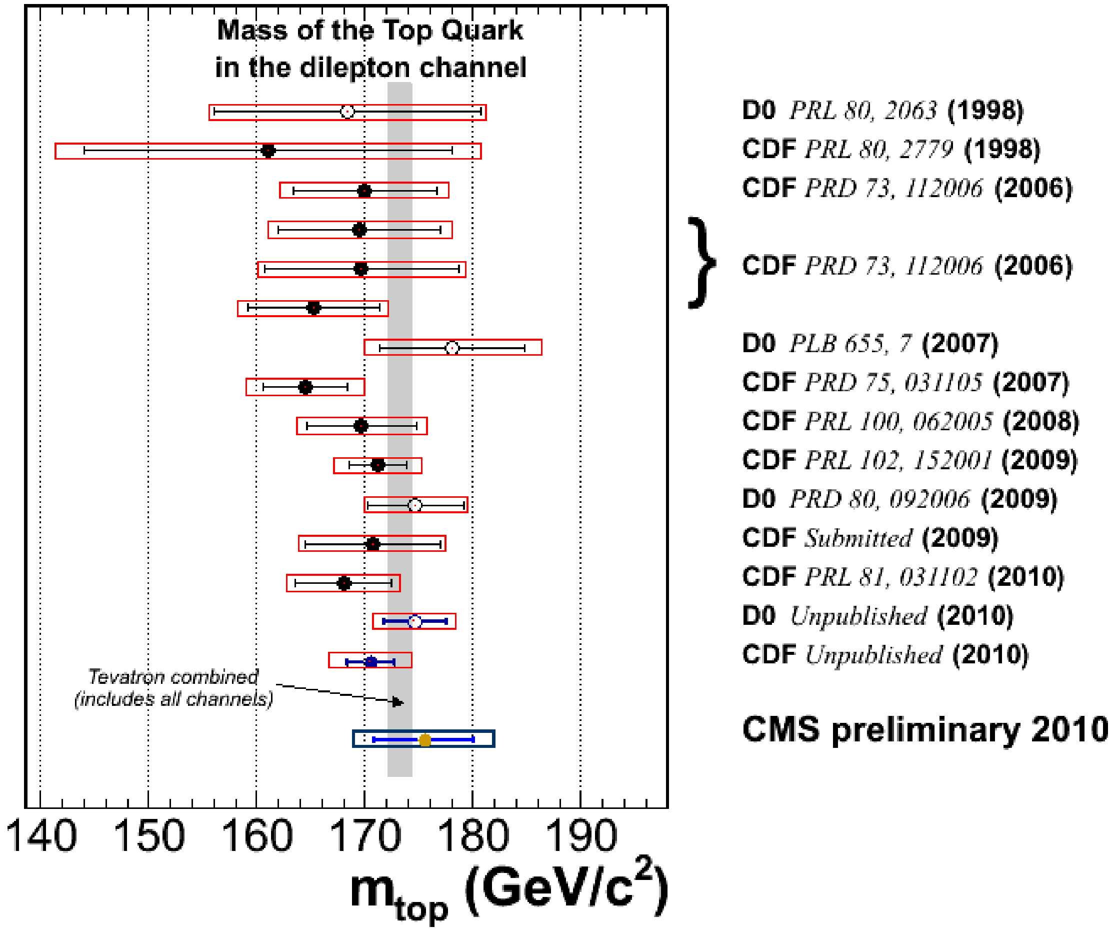


Method	Measured m_{top} (in GeV/c^2)	Weight
AMWT	$175.8 \pm 4.9(stat) \pm 4.5(syst)$	0.65
KINb	$174.8 \pm 5.5(stat)^{+4.5}_{-5.0}(syst)$	0.35
combined	$175.5 \pm 4.6(stat) \pm 4.6(syst)$	χ^2/dof=0.040 (p-value=0.84)

Conclusions

- **First top quark mass measurement which was not performed at the Tevatron**
- The **dilepton channel** is used
  - **Lower background** contamination
  - **Underconstrained system**
- Two different **template-based methods** compared: KINb and AMWT
  - Similar uncertainties (stat. and syst.) expected in both cases
  - Use of b-tagging information and combination of fits improves resolution



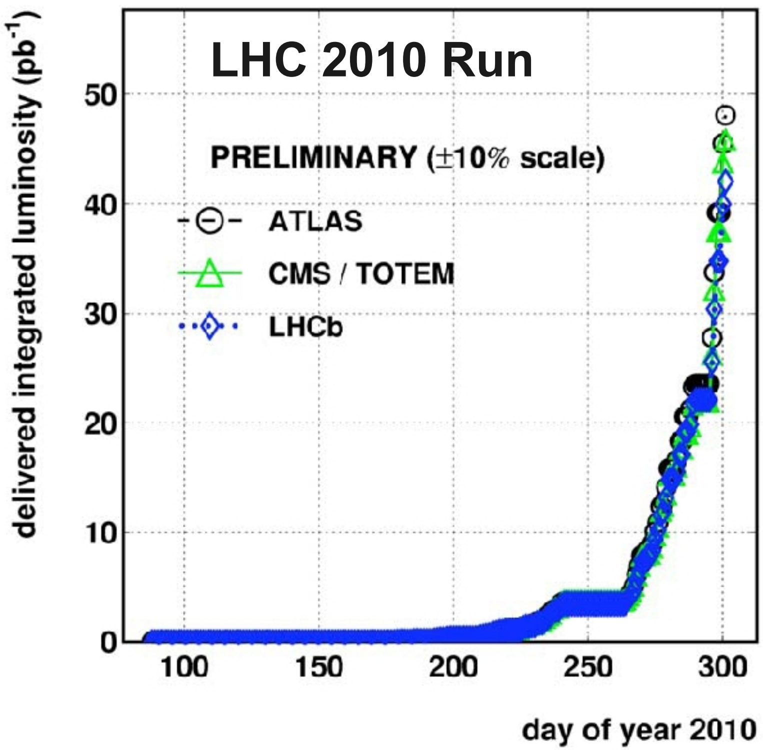
Measurement is the outcome of the first year of data taking/analysis in CMS

All details in CMS-PAS-TOP-10-006

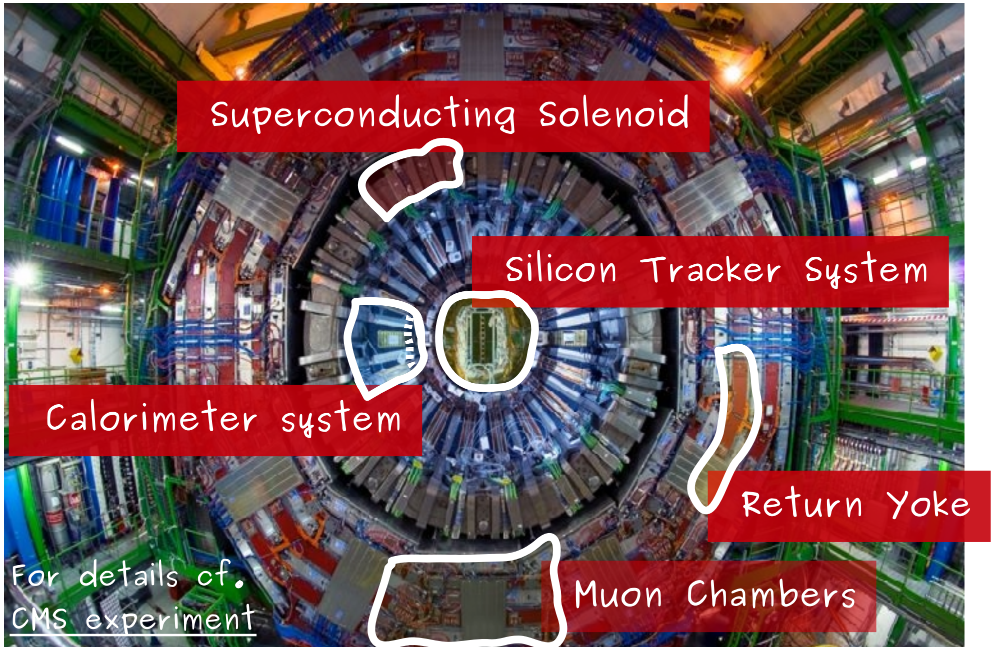
Backup slides

The collider and the detector

- **LHC : p-p collisions at $s^{1/2}$=7 TeV**
  - Total integrated lumi. **delivered: 50 pb^{-1}** (half of it in one week)
  - Peak luminosity: 205 $\mu b/s^{-1}$

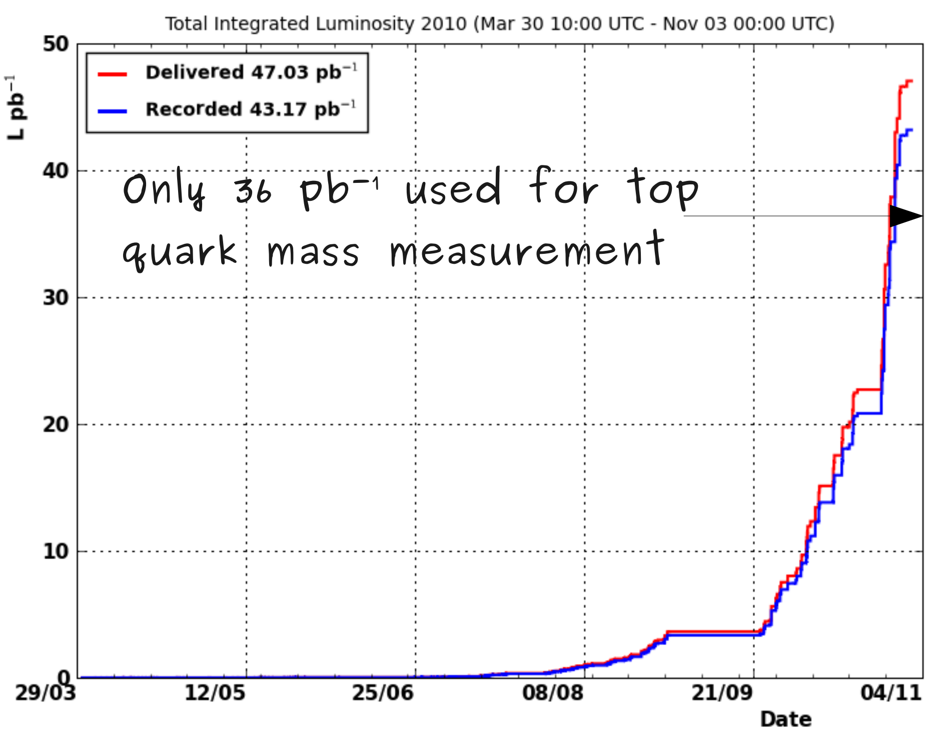


- **Compact Muon Solenoid (CMS)**
  - Collected 93% of the delivered luminosity *(L_{acq}≈43 pb^{-1})*
  - Sub-detectors operational >99% of the run period
  - More details see K. Hoepfner's talk

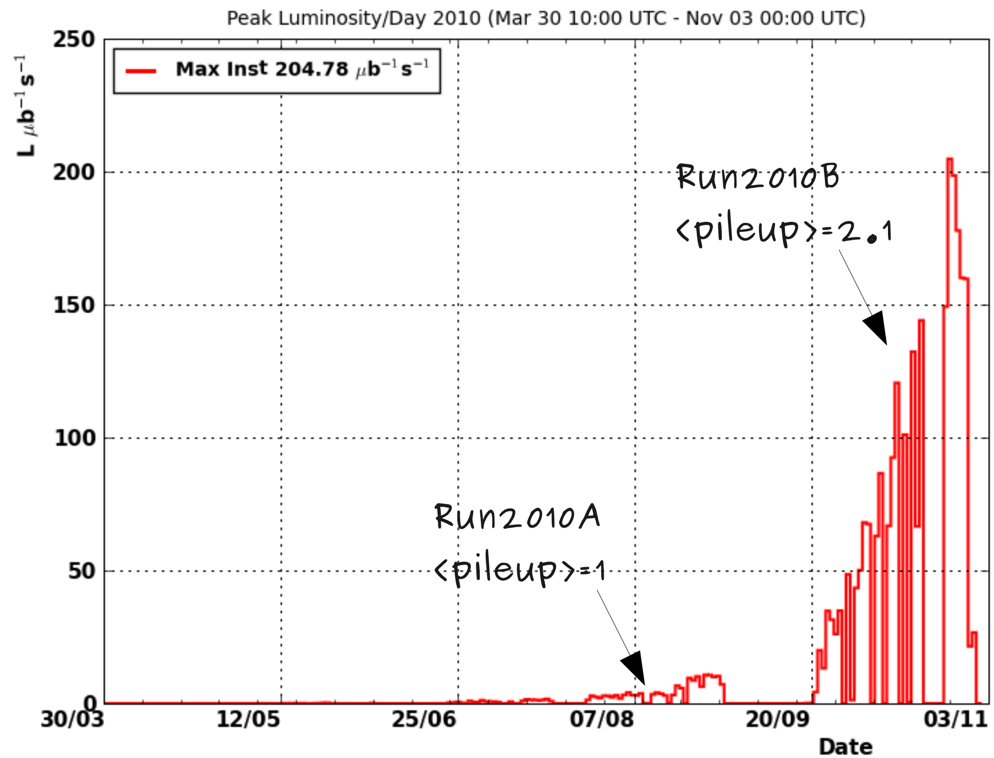


CMS Luminosity for 2010 data

Total Integrated Luminosity



Maximum Instantaneous luminosity / day



- **Estimated from the energy deposition in the Forward Hadronic calorimeter**:
  - Average number of towers without energy deposition μ mean number of interactions / bunch
  - Average transverse energy μ luminosity
- An **uncertainty of 4%** has been estimated for the 2010 measurements

Not relevant for m_{top}

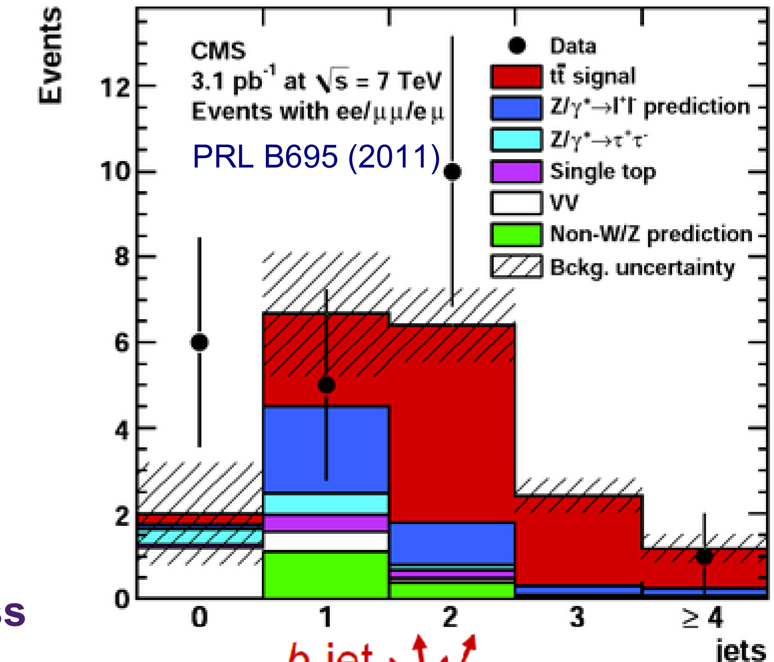
Top quark Physics

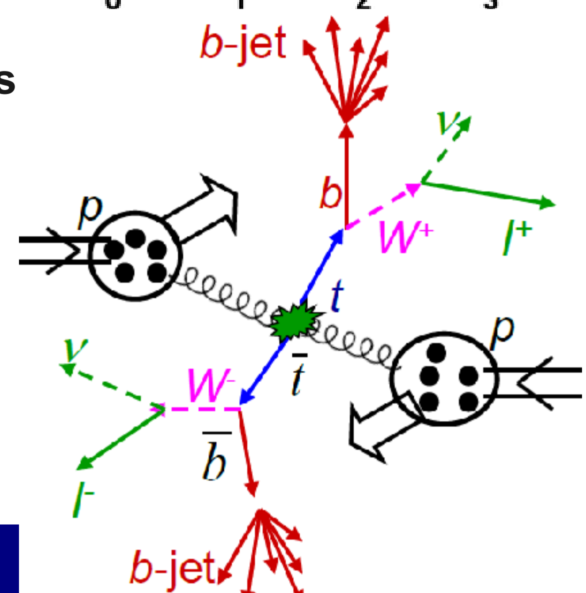
- **Re-discovered at the LHC with early 2010 data ▸**
  cf. most recent measurement in Julien Caudron's talk

- **Production in pairs is the dominant channel**
  - Dominant channel: gluon-gluon fusion
  - $\sigma_{t\bar{t}}^{\mathrm{NNLOapprox}}(m = 173\,\mathrm{GeV},\ 7\,\mathrm{TeV}) = 163^{+7+9}_{-5-9}\,\mathrm{pb}$ PRD 82 (2010)

- Top quarks **decay promptly** without hadronizing
  - Reconstruct final state products ⇒ **reconstruct bare mass**
  - B(t → bW) ≈100% ⇒ **2 b-jets + leptons / neutrinos / light jets**

- **The dilepton channel ▸**
  - Lowest statistics BR ≈ 5/81
  - Leptons are produced promptly, are isolated and have high p_T
  - **Background is small**





Other challenges in measuring m_{top}

- **Top pair production is rare**: $\sigma_{t\bar{t}}/\sigma_{pp} \approx 2 \times 10^{-9}$ $\Rightarrow$ event selection is crucial

- **Background processes** may mimic top pair decays

Process	$\sigma_{t\bar{t}}/(\sigma \cdot BR)$	Jets	Heavy flavor	Isolated leptons	E_T^{miss}
QCD	$\approx 10^{-9}$	multijets	$b\bar{b}$	-	instrumental
W	≈ 0.005	ISR/FSR	$b\bar{b}/c\bar{c}$ assoc. prod.	1	from $W \to l\nu$
Z	≈ 0.05			2	instrumental
Di-boson	≈ 2.1		from W/Z decays	≥ 2	from $W \to l\nu$
Single top	≈ 3.8	≥ 2 jets	1 b-jet	≥ 1	from $W \to l\nu$

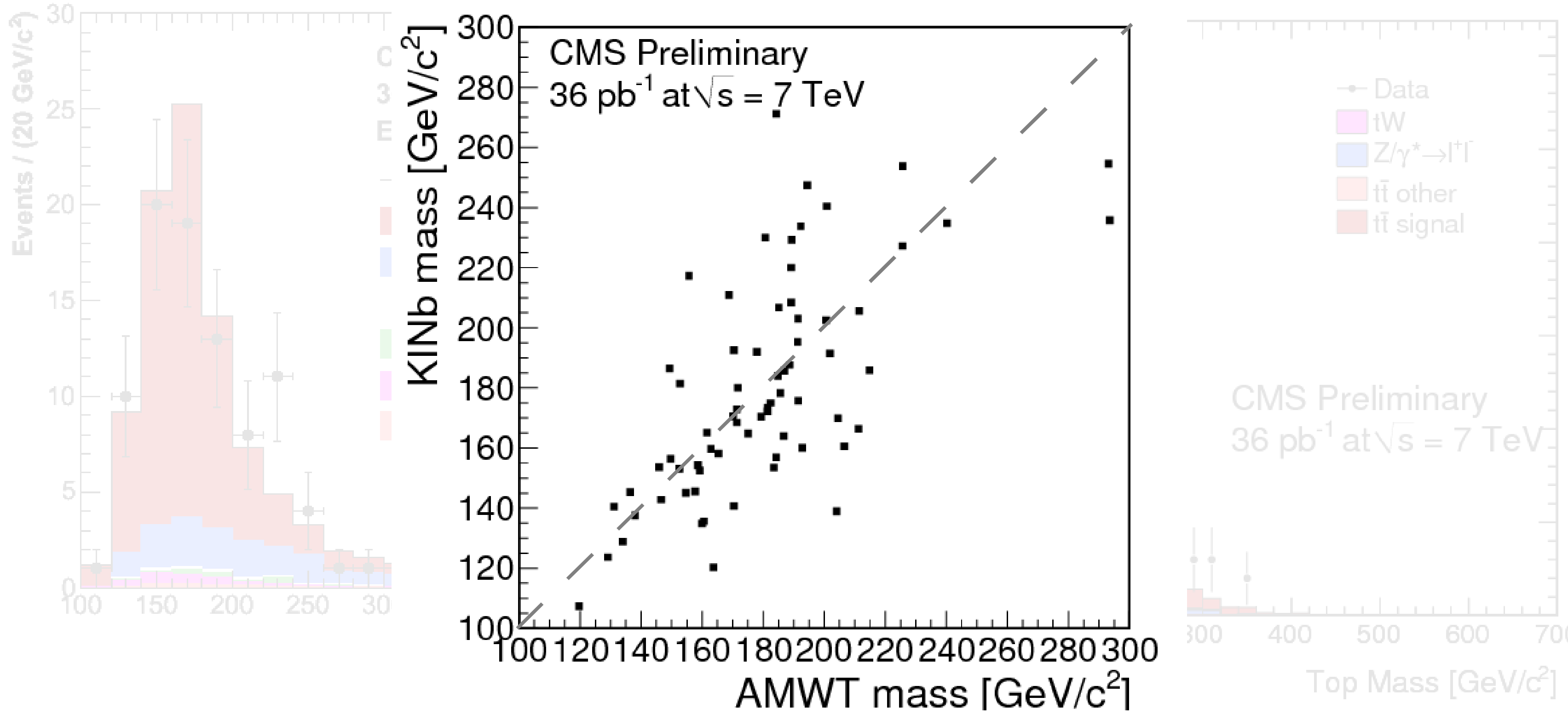
  - Events with 2 isolated leptons are the main source of background to the dilepton channel

- **Pileup may introduce uncertainties**
  - jet energy scale, MET measurement, extra jets/leptons
  - $\langle N_{pileup} \rangle \approx 2.1$ for most of the data collected in 2010

Top mass distributions

KINb

AMWT



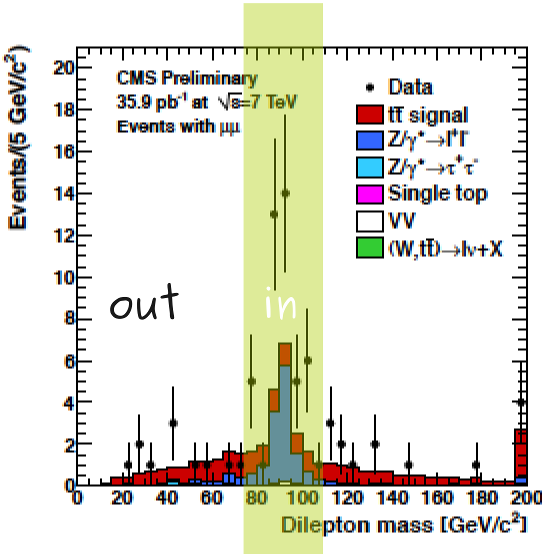
For top mass measurement restrict to 100<m<300 GeV/c²

Data-driven estimate of Drell-Yan contamination in the dilepton channel

cf. TOP-10-005

- For ee/μμ : **DY contamination outside Z-peak** is projected from events found inside

$$N^{ee,\mathrm{data}}_{\mathrm{out}} = \overbrace{R^{ee}_{\mathrm{out/in}}}^{\text{ratio outside/inside from } DY \text{ simulation}} \left(N^{ee,\mathrm{data}}_{\mathrm{in}} \underbrace{- 0.5 N^{e\mu,\mathrm{data}}_{\mathrm{in}} k_{ee}}_{\text{correction for non-DY contribution in } Z\text{-veto region from } e\mu \text{ sample}} \right)$$



- **Expect good agreement from MC**
  - Ratio depends on jet multiplicity and MET

    ⇒ assign **variation** as **systematic** unc.

Sample	$N_{\mathrm{jet}} = 1$	$N_{\mathrm{jet}} \geq 2$
e^+e^-: $\not{E}_T > 50$ GeV in $N_{\mathrm{jet}} = 1$, $\not{E}_T > 30$ GeV in $N_{\mathrm{jet}} \geq 2$		
Simulated	0.1 ± 0.1	1.7 ± 0.3
$R_{\mathrm{out/in}}$	0.13 ± 0.13	0.14 ± 0.03
Estimate from data	0.2 ± 0.3	$\boxed{3.0 \pm 1.8}$
$\mu^+\mu^-$: $\not{E}_T > 50$ GeV in $N_{\mathrm{jet}} = 1$, $\not{E}_T > 30$ GeV in $N_{\mathrm{jet}} \geq 2$		
Simulated	1.4 ± 0.3	3.3 ± 0.5
$R_{\mathrm{out/in}}$	1.1 ± 0.3	0.22 ± 0.03
Estimate from data	5.2 ± 3.4	$\boxed{7.4 \pm 4.1}$

- Method estimates an **excess of DY in data** ▸
  - Scale factor ~ 2 for both channels
  - in the table: statistical uncertainties only

Top mass fit

KINb

$$\mathcal{L}(m_t) = \mathcal{L}_{\text{shape}}(m_t) \times \mathcal{L}_{n_b}$$

where, $\mathcal{L}_{\text{shape}}(m_t) = \frac{e^{-(n_s+n_b)}(n_s+n_b)^N}{N!} \prod_{i=1}^{N} \frac{n_s P_s(m_i|m_t) + n_b P_b(m_i)}{n_s+n_b}$

$\mathcal{L}_{n_b} = \mathcal{G}_{\text{auss}}(n_b, \bar{n}_b, \sigma_{n_b})$

Unbinned fit, background is constrained

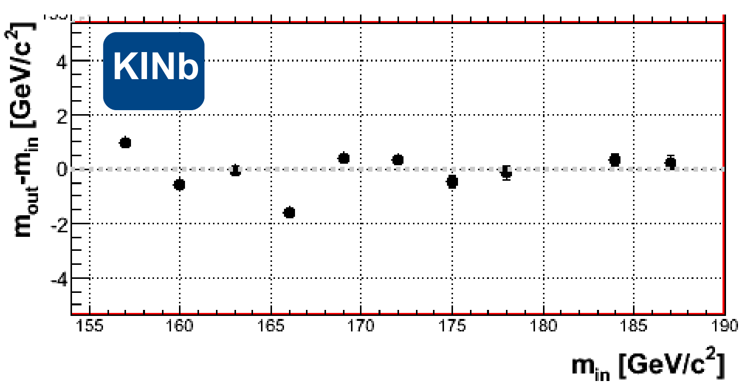
AMWT

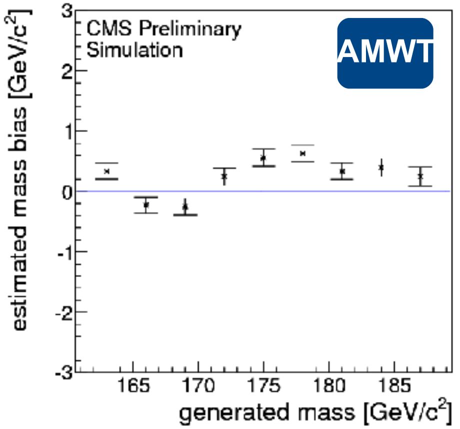
$$L(m_t) = \prod_{i=1}^{n_{\text{bin}}} \left[\frac{n_s s_i(m_t) + n_b b_i}{n_s+n_b}\right]^{n_i}$$

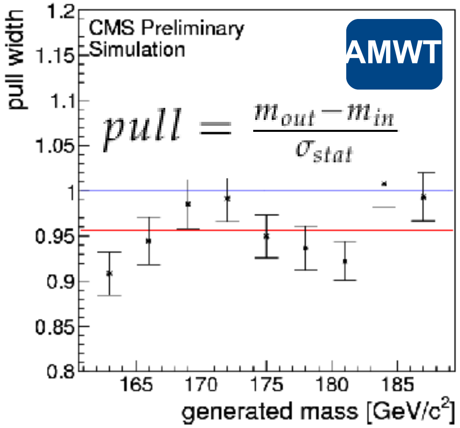
Binned fit, background is fixed

Choose mass point closest to the minimum and fit parabola to a ±12 GeV/c² neighborhood

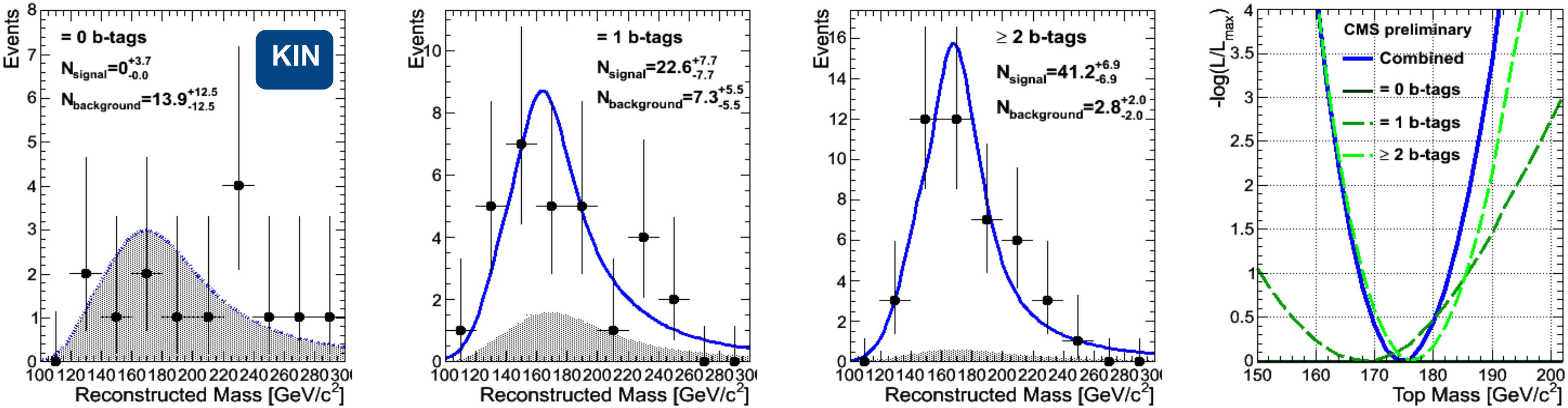
- Background introduces a extra bias (both KIN and MWT)
- Signal template parameterization introduces residual biases (KIN only)
  - KIN calibration constant: -0.7 ± 0.2 GeV/c^2

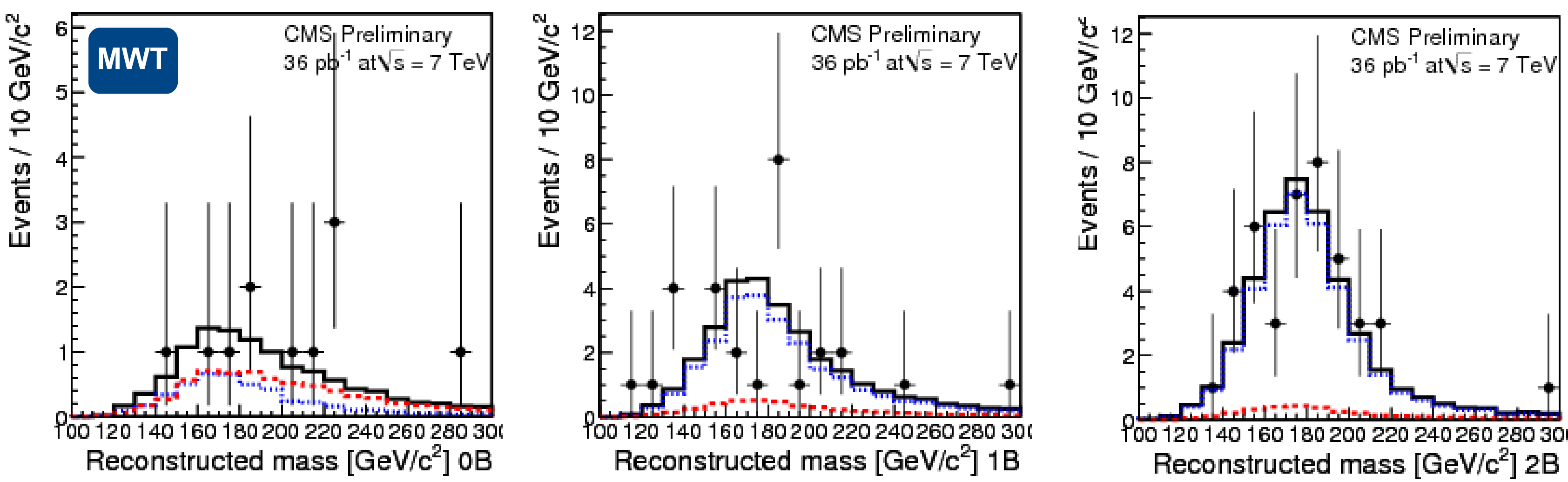






Top mass fit by categories





Summary of systematics

Source	KINb	AMWT	Correlation factor	Combination
jet energy scale	+3.1/-3.7	3.0	1	3.1
b-jet energy scale	+2.2/-2.5	2.5	1	2.5
Underlying event	1.2	1.5	1	1.3
Pileup	0.9	1.1	1	1.0
Jet-parton matching	0.7	0.7	1	0.7
Factorization scale	0.7	0.6	1	0.6
Fit calibration	0.5	0.1	0	0.2
MC generator	0.9	0.2	1	0.5
Parton density functions	0.4	0.6	1	0.5
b-tagging	0.3	0.5	1	0.4

- **JES is the dominant systematic uncertainty**
  - Cross-check by reverting measurement:
    - fix m_{top} to world average and determine <b-JES> needed to measure it
    - <b-JES> determined with an uncertainty of 4.8%
- **Underlying event / pileup** uncertainties are expected to be reduced with further understanding of LHC data and dedicated subtraction algorithm in 2011 - cf. PLB 659 (2008)
- Table shows systematics with uncertainties >0.5 GeV (many other sources were considered, e.g. lepton/MET scales)